11 / MARS

OVER THE PAST FOUR YEARS, I have spoken before many audiences on the capabilities of the Space Transportation System and the implications for space development. My talks generally follow the themes in this book and consequently emphasize exploration and utilization of the Moon. I find that almost all who have considered this topic view Mars as the long-term goal for human settlement. Schmitt capitalizes on the martian mystique to propose a national project as a symbolic theme for the technology and spirit of the new century. Many believe the Red Planet should be the next manned goal, bypassing the Moon because "we have already been there." King echoes these sentiments and lays out some arguments for that viewpoint based on scientific knowledge to be gained and the resources available for supporting exploration.

All of us have experienced traveling on the Earth and intuitively expect long journeys to take more energy and fuel than short ones. For destinations in the solar system, the bulk of the fuel is expended in the gravity field of the Earth. Therefore, a spacecraft capable of the round trip to GEO has the propulsive capacity to take payloads to lunar orbit or martian orbit. Payloads delivered to the martian system are smaller because propulsive departure from the Earth's orbit and propulsive insertion at the orbit of Mars demand additional fuel. Landing on and ascending from the surfaces of these planets requires extra capability. As O'Leary points out, the Space Transportation System of the next decades will open a variety of options for exploration, including the moons of Mars and the Earth-approaching asteroids. Since the energy calculations are based on favorable positions of the Earth and the destinations, launch windows for distant bodies are infrequent and travel times are usually long.

As awareness of the versatility of the Space Transportation System increases, consideration is being given to the role of regular missions to the martian system within that infrastructure. The deficiency of the Moon in volatile elements and water makes those materials very expensive outside the Earth's gravity well. Cordell suggests that the moons of Mars may be economically viable sources of water in

rt of activities in space. Squyres reviews a body of recent scientific thought on le of water in the geologic evolution of the planet Mars. Obviously, martian will be utilized by surface explorers, but current space development models t include planetary surface water as a space resource.

A MILLENNIUM PROJECT—MARS 2000

Harrison H. Schmitt

P.O. Box 8261, Albuquerque, NM 87198

The establishment of a permanent martian base by 2010 would be the first firm step toward human settlement of the solar system away from Earth. Such a goal should be the foundation of an international Millennium Project that will mobilize the energies and imaginations of young people who are already looking beyond Earth orbit and the Moon. Although a Mars 2000 project should be the ultimate aim of space policy for the remainder of the century, it can benefit greatly from successful efforts to create an Earth Orbital Civilization of space stations and permanent lunar bases.

INTRODUCTION

The frontier of space—this new ocean of exploration, commerce, and human achievement—has produced a level of excitement and motivation among the young generations of the world that has not been seen for nearly a century. History clearly shows us that nothing motivates the young in spirit like a frontier. The exploration and settlement of the space frontier is going to occupy the creative thoughts and energies of major portions of human generations for the indefinite future. I find totally unacceptable and totally unrealistic the view that it will be 50 to 100 years before we reach major new milestones in space. People are not going to wait that long. The only principal historical issues in doubt are the roles that will be played by free men and women and how those roles will relate to the problems of the human condition here on Earth.

The return of Americans and their partners to deep space must be viewed in the context of the nation's overall perspective of its role in the future of humankind. That role in space has not been fully formulated into a national consensus. It seems safe to say, however, that for generations now alive we will be the free world's principal agent and advocate in interweaving the ongoing Age of Information, the soon-to-be Earth Orbital Civilization and the world's Millennium Project: Mars 2000.

First of all, we must recognize the obvious. Space provides a major part of the foundation for the Information Age into which we have entered. Satellites provide the essential links in the gathering and transmission of information on a world-wide basis. Reinforced by the advent of modern automatic data processing, weather forecasting, resource identification and monitoring, information systems and general telecommunication systems, satellites and transoceanic cables have created an expanding central nervous system for the planet Earth. This system not only provides a means for dramatically increasing the well-being of all people—particularly those in the less developed countries—but also for keeping the peace.

Second, the unique resources of near-Earth space provide the basis for the creation of an Earth Orbital Civilization. The weightlessness, the high vacuum at high pumping

rates, and the unique view of the Earth, Sun, and stars can be utilized for industrial, public service, educational, research, and peacekeeping purposes. These new "resources" are not only accessible to Americans, but to all the free peoples of the world if we are willing to act as their agent.

Finally, the Moon and planets offer both challenges and opportunities to excite existing and future generations of free men and women just as the New World offered both challenge and opportunities to past generations. The extension of our civilization of freedom to the planetary shores of the new ocean of space should be our basic rationale for the world's Millennium Project: Mars 2000. With the successful completion of this project, namely, the establishment of a permanent martian base by 2010, we should see the first firm steps toward permanent human settlements away from Earth.

Our consideration of a return to deep space should take into account the requirements and realities of each of these phases of our national and international role in space. In short, there is as much need for a "Chronicles Plan" now as there was in 1978 when it was first proposed to the Carter Administration and the Congress (Schmitt, 1978).

THE INFORMATION AGE

The Soviet Union shocked the world in 1957 when it simultaneously launched the first artificial satellite of the Earth and the Age of Information. I was an exchange student in Norway at the time and observed firsthand the profound impact this event had on the international student community then in residence at the University of Oslo. There was wonder at this first reach by mankind into the new ocean of space; there was fear that the oppressive Soviet civilization would dominate humankind through use of its new technological prowess.

The collection and distribution of information on a worldwide basis via satellite has provided a distinct change in the course of human history. The most graphic demonstration of this change came when, on Christmas Eve, 1968, hundreds of millions of human beings throughout the world simultaneously had new thoughts about a familiar object in the night sky—the Moon. The men of Apollo 8 were there, and the Moon would never be the same for anyone. Now we realize that the world will never be the same. The Information Age can provide solutions to those age-old problems of the human condition on Earth if we are wise enough to reach out and grasp them.

Information systems technology, in the broadest sense, makes it possible to rationally imagine the gradual elimination of hunger, disease, poverty, and ignorance in underdeveloped portions of the world. These four horsemen of disaster are rushing down on humankind and freedom at unparalleled speeds. However, for the first time in human history, we can consider technically realistic means of stopping their onslaught.

Through information technology and know-how we can and should help underdeveloped nations create agricultural, health, resource, and educational systems that permit their entry into the economic twentieth century. As an astronaut traveling in Africa, Asia, and Latin America, I heard one message from those who do not want dictatorships of either the right or the left. "Send us know-how, not dollars. Dollars

just go into the pockets of our leaders; know-how will go into our minds." This is what the Age of Information is all about.

The race to the Moon and the goal of putting men there and returning them safely to Earth provided the intellectual and technological stimulus for the ongoing information revolution. The establishment and support of deep space bases and settlements will provide continued incentives for the improvement of technologies related to computers, automation, data processing, systems longevity, and telecommunications. All such technological improvements, as well as the international collaboration involved in creating them, will increase the leverage we have to remove the underlying causes of much of the world's unrest that threatens the lives and well-being of its inhabitants.

In the crucible of modern history there are several significant but far too few foreign policy experiments showing that efforts by the United States to transfer know-how can be both successful and well received. For example, there was the early Peace Corps, before well-meaning but inexperienced college students replaced the highly motivated and knowledgeable American professionals from all walks of life that gave so much of themselves. There is the training in telecommunications provided by U.S. industry on behalf of INTELSAT and revived today by the privately sponsored United States Telecommunications Training Institute. There is educational cooperation such as that between New Mexico State University and the technical colleges of Mexico. There is the provision of national technical services and training through contracts between U.S. industry and Third World countries.

Such activities should be the wave of the future rather than the exceptions of the past. With their expansion, there finally can be hope that moderate political forces for freedom can replace the totalitarian forces for oppression.

EARTH ORBITAL CIVILIZATION

The tangible beginnings of the creation of an Earth orbital civilization came with the launch of Skylab in 1974. The Skylab missions, followed by those of Salyut, Spacelab, and the Space Shuttle, began the examination of many of the potential uses of the resources of near-Earth space. Skylab gave direction to our imagination about the use of these resources. The Salyut, Spacelab, and the Space Shuttle now give license to our imagination. Space stations will give reality to this imagination.

The resources of a near-Earth space civilization are basically three in number: (1) instantaneous and continuous view of the Earth, the Sun, and deep space; (2) an infinite quantity of clean, ultra-high vacuum at high-pumping rates; and (3) a weightless environment, that is, an environment free of most gravitational stress.

An instantaneous and continuous view of the Earth and its total environment makes possible a wide spectrum of space activities. Observatories become possible from which research and services in meteorology, oceanography, geology, and ecology can be conducted and from which broad-scale explorations for new terrestrial resources can be carried out. Man's application of his eyes, his mind, and his imagination to the direction of remote-sensing systems presently has unlimited potential to benefit humankind.

The Sun remains the major contributor to the stability and the changes of our magnetic, atmospheric, oceanic, and biological environments. However, our knowledge of how the Sun's energy and magnetism influence changes in our environment is extremely limited. A continuous view of the Sun outside the shielding effects of the Earth's atmosphere will first give us understanding of processes taking place on and in the Sun and of the nature of their interactions with the Earth. Then, eventually, this view will form the foundation for forecasts that will protect against, or take advantage of, the effects of interactions between Sun and Earth.

One of our greatest sources of intellectual strength and scientific vitality is in continued observation of the universe and attempts to understand the stars and interstellar space. The greatest discoveries of the future probably lie in investigations of stellar and interstellar phenomena. The nature of gravity; the origin of plants; the limits on our ability to manipulate matter, energy, and time; and our future as explorers of the universe are all issues at stake.

Nearer to home, major limitations to experimentation and manufacturing in many areas of physics and chemistry exist on Earth because of the difficulty in maintaining clean, ultra-high vacuums in large volumes. The existence and accessibility of such a vacuum resource in near-Earth space open new dimensions in the study and use of physical and chemical theory.

The continuous absence of gravitational stress, that is, weightlessness, provides a unique experimental and practical environment heretofore unavailable to man. Extensive experimentation and manufacturing has never before been possible where convection does not exist, where containers for fluids are not required, and where gravitationally unconstrained crystal or biological growth can occur. The absence of gravitational stress means that no containers are required to hold the experimental materials. Thus, new investigations of the dynamics and properties of fluids and materials formed from fluids and emulsions are now feasible. These investigations, along with other basic research in physics, chemistry, and biology, are leading to commercial applications in space manufacturing facilities.

Further, in medical laboratories in space we now can look continuously and in great detail at cell, animal, and human growth and function in the absence of gravitational stress. We can also look at the applications of such an environment in medical treatment and recovery as well as in the production of medicine. This is probably the appropriate place to point out that those men and women who are handicapped by gravity on Earth will have no significant handicap in the weightless environment of space. They can be just as productive living and working in this environment—where movement is accomplished merely by the push of a finger—as can those who are not gravitationally handicapped.

Finally, let us consider the possibility of a space education facility where one can conceive of students of all ages participating, limited only by interest and minor physical criteria. One now can conceive of spaceflight for students of all disciplines from the nuclear physics major to the medical student to the poet or novelist. One also can conceive of students in space who represent all nationalities and who will continue the great traditions of space that bring people and nations together.

The stimulation triggered in young minds by a week or summer in space defies the imagination. The fact that we can now consider education in space as a rational possibility is a measure of what transpired in the two decades of Apollo, Skylab, Salyut, Spacelab, and Shuttle. A change of course has been made; each generation, ours and those that follow, must determine what exact course to chart, but proceed we must; history does not allow us to stand still.

A return to deep space and the establishment of lunar and planetary settlements can play an extraordinarily important role in an Earth Orbital Civilization. The potential resources that can be derived from the surface materials on the Moon may well sustain both the transportation and manufacturing economics of that civilization.

The management (governance) of a lunar settlement that supports the activities of the stations of an Earth Orbital Civilization, as well as supporting its own existence, must conform not only to existing space law and precedents, but also to the cooperative urge that space endeavors have generated in the human psyche. The only practical way that this management system can come into being appears to be to follow the precedents set by the Intelsat and Inmarsat organizations. These are user-based and profit-making management systems rather than one-nation/one-vote or national systems. Such user-based systems for lunar base management, such as the Interlune proposal (Joyner and Schmitt, 1985) draw their strength from the economic self-interest each member nation has in the success of the enterprise. The integration of our own free-enterprise system with such organizations has been shown to work very well. Ultimately, we should expect a lunar settlement to become independent of Earth-based institutions as it develops diverse trading relationships and becomes largely environmentally self-sufficient.

THE MILLENNIUM PROJECT: MARS 2000

No matter what other justifications may be given, the ultimate rationale for today's generations to return to deep space and to establish a permanent presence there is to create the technical and institutional basis for the settlement of Mars. This will be the first great adventure for humankind in the third millennium after the birth of Christ.

Steadily increasing philosophical and psychological momentum for this adventure is building among the young people of the Earth. There is great privilege and enjoyment in spending hundreds of hours in the schools of America and the world talking with these future space travelers about Apollo's space experiences and listening to their view of the future. Let us examine that view more closely.

College and high school students seem to have their impressions of space flight and "what was it like" fairly well formed. Unlike most adults, however, the students of elementary school age ask questions purely and simply because they are curious. After a few encounters with adult audiences, most of the questions of succeeding audiences can be anticipated. However, one never can anticipate all or even most of the questions from students in elementary school who want to go to space.

In order to test awareness of young students, and before showing colored slides from my trip to the Moon, I ask a few questions.

To be sure of the general knowledge of the group, I ask, "What is gravity?" Lots of hands go up and the typical answer is, "It is what holds you down." Excellent answer; in fact, few adults know much more than that unless they are capable of grasping or debating Einstein's theory of general relativity.

The next question I ask is, "How many of you would like to go to the Moon someday?" About 75% of the hands of fifth-grade and younger students go up (older students are more reluctant to raise their hands if Dick and Jane aren't going to).

"Now, how many of you would like to go to Mars?" About 85% of the hands go up. Why 10% more? I asked some of those who raised their hands for Mars and not the Moon, "What is wrong with the Moon?" The answer: "You've already been to the Moon!"

Ten percent are never satisfied. Rather than the Moon, many have their eyes on Mars. They are the ones who will go to Mars. They are the ones, like most of our ancestors before them, who will never be satisfied with either the comforts or the restrictions of home and Earth. These are the parents of the first martians.

The importance to the parents of the first martians of a self-sustaining settlement on the Moon—trading directly with our Earth Orbital Civilization of permanent space stations—is that it gives us the technical and institutional basis to go to Mars with the purpose of establishing a permanent base on the first expedition. This expedition could be on its way by the end of the first decade of the third millennium. A permanent settlement will take a little longer, but a permanently occupied base—resupplied by regular interplanetary space stations—clearly will be possible as well as desirable soon after the establishment of a permanent lunar settlement and an Earth orbit space station.

Why the hurry? Why a Millennium Project that stretches our reach to the limit? The answer is in the minds of young people who will carry us into the third millennium. It is in the generations now in school, now playing around our homes, now driving us to distraction as they struggle toward adulthood. They will settle the Moon and then Mars. They will do this because they want to do this. They want to "be there." Our role is merely one of staying out of their way while we preserve and expand their opportunities.

The answer to "Why the hurry?" is also clear in the determination of the Soviet Union to establish its sovereignty in deep space and on Mars before the forces of freedom do so. Very long duration Earth-orbit flights by the cosmonauts, heavy-lift launch vehicle development, and their public emphasis on manned Mars exploration all tell us what the Soviets expect to do before the end of the twentieth century. An attempt to put Soviet cosmonauts in the vicinity of Mars by October 1992, the 75th Anniversary of the Bolshevik Revolution, is not only possible, it is highly probable. How sad if this adverse trend of political history is established in the 500th year after the discovery of America by Columbus.

Mars 2000 will be for the children of the free world what space stations were to their parents and what Apollo was to their grandparents: the total embodiment of the best in the human spirit. Maybe most importantly, if our determination is unequivocal, astronauts and cosmonauts may be able to join hands in this great adventure.

There is little technical distance between us today and the realization of all that I have suggested. Certainly, there is little to be done compared to the task that faced

us when we began the race to the Moon. Whatever technical options may turn out to be appropriate, now is the time to create those options so that the next generation may proceed when they are ready.

The first martian base will probably be established using inflatable shelters in one of the deep equatorial valleys near areas that show strong photographic evidence of being underlain by water-rich permafrost. The Valles Marineris is such a valley. The deep valleys also will provide somewhat higher temperatures and atmospheric pressure than other possible sites such as the polar regions where water-ice is clearly present. However, one of the advantages of using a large interplanetary space station for the first trip to Mars is that the time necessary to examine the martian moons for resources and to select a proper site for the first base can be spent in orbit about the planet before committing to the first landing. If necessary, reconnaissance of several sites can be carried out before committing to a site for the base.

The most inconvenient aspect of living and working on Mars will be the dust. Unlike the Moon, which has no atmosphere, dust on Mars blows around in great global storms and settles very slowly. It may be that these storms will require the temporary confinement of the explorers to shelters much like in winter at Antarctic bases.

One of the major uncertainties that Mars 2000 will have to deal with is the chemical and agricultural nature of the martian soil. It is highly probable that, like the lunar soil and new volcanic ash, the martian soil is very fertile. In fact, it may be rich in particles of clay as well as impact and volcanic glass. However, the existence of a martian atmosphere, its oxidizing nature (the "red" planet), and the possible presence of sulfur in the soil crusts may mean that some treatment of the soil will be required before it can be farmed properly. An alternative for growing food may be hydroponics, depending on the availability of sufficient quantities of water. Again, the interplanetary space station used for transport should be large enough to outfit for either of these options as well as for large quantities of "imported" food.

The confidence we can have in discussing the establishment of a permanent base on Mars comes from two directions: the confidence and knowledge gained from the Apollo expeditions to the Moon and the spectacular and detailed data returned by the Viking landers and orbiters of Mars. We know nearly as much about Mars as a planet as we did about the Moon before Armstrong and Aldrin landed there in 1969.

However, space activities will be sustained less by technology and knowledge than by emotions: the emotions of young Americans and young people the world over. Indeed, even young Soviets, East Europeans, Chinese, and Cubans also must look to space as the Earth's frontier. As with our ancestors, their freedom lies across a new ocean, the new ocean of space.

The Millennium Project: Mars 2000 is their hope as well as our mission.

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MARS: THE NEXT MAJOR GOAL?

Elbert A. King

Department of Geosciences, University of Houston, Houston, TX 77004

The next major thrust into space may be strongly tied to the occurrence and availability of extraterrestrial resources. An attempt to exploit material resources at any extraterrestrial location will require a major commitment over a period of many years. The magnitude of this commitment probably will not allow simultaneous vigorous pursuit of other major projects. Thus, it behooves us to consider our mission options carefully and to design a program that will produce access to the most needed resources, such as hydrogen, oxygen, water, carbon dioxide, and other volatiles, at locations that will help us to achieve our most important goals. The exploration and exploitation of Mars and its moons offers an attractive alternative to possible lunar options and would ultimately lead to colonization of the planet. Serious planning must be initiated soon for manned missions to Mars and its moons if we are to make informed decisions about the next few decades of human activity in space.

INTRODUCTION

Virtually everyone believes that our civilization will send manned missions to Mars and that it is desirable to do so, and authors of NASA publications predict or assume that manned exploration of Mars will occur (*e.g.*, French, 1977; Glasstone, 1968). Mars has fascinated some high-level NASA officials who have published extensively on manned missions to Mars (*e.g.*,von Braun, 1962; Ley and von Braun, 1956), but while colonization of the "Red Planet" is fondly mentioned in some studies, the actual event is usually assigned to some indefinite date in the distant future. This need not be the case! The United States space program is now committed to the construction of a space station during the early 1990s. A properly designed, low Earth orbit space station, with capability for on-orbit assembly and servicing of stages and modules, would complete the infrastructure that is needed to support manned missions to Mars.

WHY GO TO MARS?

Stated very simply, Mars is the most "user friendly" planet (for humans) in the solar system next to Earth. Because of its surface environment, scientific importance, accessibility, and abundant resources (particularly volatiles), it is a logical place for a permanent base and by far the most attractive planetary surface locality for a colony. For details of Mars' atmosphere and surface environment see Scientific Results of the Viking Project, *J. Geophys. Res., 82*, 3959–4681 (1977); *J. Geophys. Res., 84*, 7909–8544 (1979); *J. Geophys. Res., 87*, 9715–10,306 (1982). Let us enumerate some of the most attractive features of Mars.

Atmosphere

The general abundance of volatile elements on Mars and its size result in the presence of a thin atmosphere comprised chiefly of carbon dioxide with small amounts of water vapor, nitrogen, argon, and other gases. The total atmospheric pressure depends on the local elevation but averages approximately 6 mbar. This includes approximately 30 micrometers of precipitable water. The atmosphere is available everywhere on the martian surface and constitutes a resource that can be used for the production of life-supporting oxygen, potable water, and rocket fuel. The ready availability of carbon dioxide and water greatly simplifies possible agricultural activities. The presence of an atmosphere also provides the opportunity for aerobraking of spacecraft at Mars, thereby conserving fuel and total launch weight for missions outbound from Earth. In addition, the atmosphere provides complete protection from micrometeorites and, in fact, offers protection from meteorites up to several hundred grams in size! This atmosphere has provided Mars with a weathered surface that probably contains hydrated minerals and may contain other surface or near surface ore deposits such as weathering products, lag, placers, and evaporites. Because of the atmosphere, Mars has a certain amount of weather. Although occasionally adverse, weather conditions may serve to provide psychologically satisfying changes for the expedition members.

Size and Rotation

Mars' size, between that of the Earth and Moon, resulted in a geologically more active planet than the Moon. Such familiar features as many large volcanic constructs are clearly seen and mapped on the martian surface. How late this activity continued into Mars' history is not known, but the implied high level of volcanism probably provided greater opportunity for the occurrence of certain types of ore deposits, *e.g.*, hydrothermal ores, than on the Moon. The mass of Mars provides surface gravity of about 0.4 g, a comfortable and easy working environment. Mars' rather rapid rotation not only causes some weather, but results in a day/night cycle similar to that of the Earth that humans are likely to find familiar and easy for living adaptation.

Polar Caps and Permafrost

We know that there are large accumulations of volatiles, particularly water and carbon dioxide, in the martian polar caps. These volumes are so large as to constitute a virtually inexhaustible supply. Although the extents of the polar caps vary seasonally, they still contain at maximum recession sufficient volatiles for virtually any conceivable use. There is much visual evidence of volatiles, probably permafrost, in the shallow martian subsurface as shown by certain crater morphologies, patterned ground, and large effluent channels.

Surface and Shallow Subsurface Rocks

Photogeology from orbital imagery (Mutch *et al.*, 1976; Carr, 1981; also see the previously noted general information on Mars) reveals that many of the surface rocks of Mars are volcanic. Some of the volcanoes strongly resemble terrestrial basaltic volcanoes, and it is possible that more silica-rich differentiates are present. In addition, there are

many wind-deposited sediments on the surface and, by inference, sedimentary rocks. The Viking landers provided us with chemical analyses of these sediments at two localities. Also clearly visible on Mars are impact craters of a wide range of sizes, which ensures the presence of rock glasses and fragmental debris commonly associated with such craters.

Arguments have recently been made that some meteorites, *i.e.*, SNC meteorites of basaltic affinities, originated as impact ejecta from Mars (Nyquist, 1983). Thus, we may have samples of some martian rocks already available for study. In any case, it appears that the range of surface compositions and, hence, variety of surface resources, is at least as great as the Moon and probably much greater.

Scientific Interests

While the scientific cream has already been skimmed off the top of lunar studies by the Apollo and Luna Programs, Mars still awaits detailed scientific exploration. Important questions remain about Mars relative to biological sciences. There is still the possibility of present or past martian life forms, although none were detected by our Viking landers and the prospects for a positive result do not appear encouraging. Planetary scientists are eager to establish martian geological and climatological history and to make comparisons with the Earth and Moon. Detailed investigations of the atmosphere, polar caps, and the results and dynamics of their interactions with the surface and subsurface await us on Mars. The list of physical sciences measurements desired is too long to be enumerated here, but it is much longer than that for the Moon because Mars is a much more complex planet (Mutch *et al.*, 1976; Carr, 1981; and previous note).

Phobos and Deimos

Mars has two moons that are important objects for scientific exploration in their own right. Most planetary scientists believe them to be captured asteroids. Their own albedos and densities indicate that they probably are composed of primitive, water-bearing carbonaceous chondrite material. Thus, they not only provide possibly important mission options for reconnaissance of the martian surface but offer the possibility of providing another source of mission expendables such as water, oxygen, and rocket fuel (O'Leary, 1984). Because of the low total energy required for a round trip from low earth orbit, as well as scientific and exploration considerations, Singer (1984) has proposed an early manned mission to Phobos and Deimos.

Public Interest

Mars is well known to the public. It has been popularized by science and science fiction alike for decades, *e.g.*, Percival Lowell, Carl Sagan, Buck Rogers, Edgar Rice Burroughs, Orson Welles, *etc.* Nonetheless, Mars is new! Men have not set foot there. The pure excitement of exploration will capture the public imagination as it did with Apollo. A return to the Moon would not stimulate such interest, but humans on Mars will.

Even with all of its attractive features, the low temperatures of the martian surface, lack of free oxygen in the atmosphere, and radiation background render Mars an extremely harsh environment for human habitation. Even so, it is a far better environment than the Moon!

HOW ACCESSIBLE IS MARS?

Mars is closer than you believe. In terms of propulsion energy, a round-trip mission to a moon of Mars from low Earth orbit requires less propulsion energy for an equivalent mass spacecraft (assuming aerocapture at Mars and Earth) than does a round-trip mission to the surface of the Moon (assuming aerocapture at Earth). With the same aerocapture assumptions, a round-trip mission to the surface of Mars requires a delta V of only approximately 1400 m/s more than a round-trip mission to the surface of the Moon. A detailed summary of the energies required for various mission options is given by O'Leary (1984). The difference is in travel times and frequency of launch opportunities. A one-way trip to Mars on a minimum energy trajectory requires approximately 270 days, while a one-way trip to the Moon requires only approximately 3 days. Launch opportunities to Mars from Earth are far less frequent than for the Moon, as are return opportunities. These and other considerations result in a general requirement for larger and more massive spacecraft for missions to Mars than to the Moon.

For any long duration, manned space mission we will require development of reliable long-term life support systems, whether going to the Moon or to Mars. The place to test such systems is in low Earth orbit as the Russians have done in recent years. Also, biomedical research must identify exercise, diet, and other factors that will prevent significant physiological deterioration during long periods of reduced gravity, and/or spacecraft must be designed to include artificial gravity systems. Adequate radiation protection must be provided for long duration flight crew members. This might be provided by covering most of the exterior of the crew compartments with bagged rock material collected at Phobos or Deimos and returned to low Earth orbit by an unmanned mission. Although manned Mars missions are possible with conventional hydrogen/oxygen propulsion, consideration should be given to the development of higher specific impulse propulsion systems, which would greatly enhance missions to deep space by shortening trip times and expanding launch opportunities. It appears that these developments are solvable engineering and medical problems, not greatly more complex than those that have been solved in many previous space flight programs. If the space station were to evolve into the assembly and servicing platform that we need for mission operations, we would then have all of the required infrastructure to support the manned exploration of Mars—except for the most important ingredient of all—a bold political decision!

NEW SPACE RACE TO MARS?

A new "space race" to Mars has already begun! The Russians are well along the way to a capability to send humans to Mars. A similar opinion has been expressed by Paine (1984). Their long duration Earth orbit missions have qualified their life support systems for deep space missions. The Soviet interest in Mars is long standing, as witnessed by their "flotilla" of four spacecraft launched to Mars in 1973 and their earlier efforts. The Russians have announced their intention to send an unmanned mission to Phobos/Deimos in 1988. Furthermore, their development of large lift rockets will provide them with the ability to deliver large payloads to low Earth orbit and beyond.

The United States is not completely unprepared for this race. We have explored Mars with eight unmanned probes including three flybys, three orbiters, and two landers. We know more now about Mars than we knew about the Moon when the Project Apollo decision was made. We should not view our present second place in this race with undue alarm. After all, the winner of every peaceful space race is the human race, and there is always the possibility of international cooperation in space projects. Also, the race to Mars will not be won with a single manned landing as was the race to the Moon. The race to Mars will be won by the nation whose human expedition arrives at Mars with the means and the will to stay!

CONCLUSIONS

Most importantly, we must initiate serious planning for human missions to Mars. These plans must include mission profiles, engineering concepts, technology assessments, and cost analyses. These studies should constitute an important part of the basis for an informed political decision in the near future that will identify our national goals and future programs in space.

The design of the planned low Earth orbit space station should allow the flexibility to add facilities for the assembly and servicing of large interplanetary manned spacecraft.

We must continue to expand our Mars research and resource evaluation programs. This data base will continue to be of great value for mission planning.

Without the benefit of the actions above, we run the serious risk of making a decision that, in effect, will cede Mars to the Soviets for decades!

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RATIONALES FOR EARLY HUMAN MISSIONS TO PHOBOS AND DEIMOS

Brian O'Leary

Science Applications International Corporation, 2615 Pacific Coast Highway, Hermosa Beach, California 90254

S. F. Singer proposed that Phobos and Deimos be manned bases for unmanned Mars exploration. A second rationale, described herein, concerns using the resources of the martian moons to lower the cost of the missions and to accelerate the onset of space industrialization utilizing non-terrestrial materials. This paper presents estimates of the ballistic velocity increments required to rendezvous with the two satellites, depart, and return to the Earth. When aerobraking at both Mars and Earth are considered, Phobos and Deimos are considerably more accessible in Δv than are the lunar surface, the martian surface, and most known Earth-approaching asteroids. Launch windows from Earth are usually more frequent than for the most accessible asteroids. Because of their low albedoes and mean densities, both satellites are likely to be carbonaceous, with large quantities of easily accessible water. Phobos and Deimos are ideal early resource targets and Mars exploration bases. These considerations suggest that the martian moons be early destinations that could dovetail two important goals in future space activity: the exploration of Mars and materials recovery.

S. F. Singer (1984) presented a scientific rationale and plan for the manned exploration of Phobos and Deimos (PhD) and subsequent unmanned exploration of the martian surface. The PhD mission, wrote Singer, would provide a number of advantages over either sending unmanned rovers or people directly to Mars first. One, telemetered control of rovers from the Mars-facing sides of the satellites serving as stable platforms will shorten the response time from fifty minutes to less than 0.2 seconds. Two, surface and sub-surface martian samples can be recovered at disparate sites by remote control and examined in a PhD laboratory rather than having to resort to a sophisticated laboratory on Mars or to run the risk of back-contamination by direct sample return to the Earth. Three, PhD-controlled surface rovers allow for sequential exploration of Mars at several locations rather than a single-mission, one- or two-location direct shot that may miss the most interesting spots (Viking and Apollo suffered from this problem). Four, unmanned landings are easier, less costly, safer, and could be done much sooner. And fifth, we could directly sample these mysterious moons to determine their history and fate, gaining valuable insight on the origin and evolution of small bodies in the solar system.

Adelman and Adelman (1984) have presented advantages of using Phobos as a base for gravity wave astronomy, radio astronomy, astrometry, and the study of asteroids and comets. Also, a Mars-pointing telescope on Phobos will permit resolutions an order of magnitude or more greater than that of the Viking orbiters (Sagan, personal communication, 1984).

O'Leary (1981, 1983, and 1984) has investigated the resource potential of the martian moons and their accessibilities. Both scientific and resource rationales are summarized

in this paper. The Soviets are planning an unmanned reconnaissance mission to Phobos in 1988 (Covault, 1985). Clearly, the incentive to explore and utilize the satellites of Mars is increasing.

The very low mean densities of both moons (~2 g/cm^3) and their low reflectivities are strong indicators of a chemical content similar to that of the volatile-rich carbonaceous chondrite meteorites (Veverka *et al.*, 1978). If this is true, easily extractable water is likely to be found on both moons.

Previous studies have examined the rationale (O'Leary, 1977, 1983, and 1984) and mission scenarios (O'Leary *et al.*, 1979; O'Leary, 1983) for setting up resource recovery operations on selected Earth-approaching asteroids during special launch opportunities. The martian moons can also be considered as Earth-approaching asteroids with mining potential and the added features of more accessibility of volatiles and the opportunity to explore Mars. The most accessible known asteroid, 1982 DB, offers slightly better opportunities at decade intervals, but missions in the intervening years deteriorate rapidly (Hulkower, written communication, 1982).

Earlier studies (O'Leary *et al.*, 1979; Staehle, 1983) have also pointed out that, in terms of the energy (and cost) of setting up an oxygen-extracting plant on a non-terrestrial body, the presence of water and other volatiles is far more preferable than the chemical processing of metal oxides that predominate in the lunar soil and many meteorite classes. Carbonaceous materials also make available hydrogen, carbon, and nitrogen—elements that will become useful for refueling and life support.

In the long run, the absence of these materials on the Moon or asteroid would necessitate expensive resupply from the deep gravity well of the Earth. Cordell (1984) has estimated that the energy cost of delivery of water to lunar base from Phobos and Deimos would be approximately 3 times less than that delivered from the Earth's surface.

The ballistic velocity increments (Δv) required to rendezvous with Phobos, depart, and return to the Earth have been estimated (Von Herzen, written communication, 1979). Table 1 shows the results for average launch windows from Earth every two years, assuming

Table 1. Mission Opportunities to the Most Accessible Known Extraterrestrial Resources

Target	Launch Date (or Frequency)	Round-Trip Travel Time	Velocity Intervals ΔV (km/s) Escape	Rendevous (Land)	Depart	Total*
Lunar Surface	Frequent	≳ 7 Days	3.2	2.7	2.4	8.3
Martian Surface (Atmospheric Braking)	Every 2 Years	≳ 2 Years	3.6	≳1.0	≳5.6	≳10.2
Phobos and Deimos	Every 2 Years	≳ 2 Years	3.6	1.9	1.8	7.3
Phobos and Deimos (Mars Aerobrake)	Every 2 Years	≳ 2 Years	3.6	≳0.5	≳1.9	≳6.0
Asteroid 1982 DB	Sept. 2001	4 Months	3.2	5.8	4.3	13.3
Asteroid 1982 DB	Jan. 2001	2.0 Years	4.3	0.8	0.5	5.6
Asteroid 1982 DB	Dec. 2001	2.1 Years	4.5	0.5	0.7	5.7

*These figures assume aerobraking at Earth.

Hohmann transfer ellipses between circular, co-planar orbits. Primarily because of the eccentricity of Mars' orbit, the figures for each launch window will vary up and down from the values reported here, but they are representative values for mean opportunities, as indicated by cross-checking with analyses of specific mission opportunities (Staehle, 1983; Hoffman and Soldner, 1984).

Table 1 shows that the total mission velocity increment for Phobos, Deimos, and other targets can be divided into three principal maneuvers: escape from low Earth orbit onto the transfer ellipse, rendezvous with Phobos/Deimos either by an impulsive maneuver near Mars or by a circularization after one or more aerobraking maneuvers at the top of the martian atmosphere and return on a transfer ellipse to the Earth with either aerobraking reentry, aerobraking injection into low Earth orbit, or an impulsive braking at low Earth orbit. Alternatively, a Venus gravity assist inbound or outbound would shorten the total mission time to $\lesssim 700$ days with similar total Δv's (O'Leary, 1985).

A large benefit comes from aerobraking at Mars. Once aerocapture is achieved, either through one pass or successive passes through the martian atmosphere, the Δv required to circularize at Phobos is 590 m/s and at Deimos, 667 m/s. The alternative is to break impulsively in the vicinity of Mars to eliminate the excess hyperbolic velocity, change planes, and then rendezvous with the satellites. These maneuvers consume a Δv to 1.5–2.0 km/s.

Aerobraking would also be used upon returning to the Earth or Earth orbit. Current studies of orbital transfer vehicle (OTV) systems to be used in the post-1996 time frame show an aerobrake capability (Hoffman and Soldner, 1984; Walberg, 1983). Because the velocities of atmospheric encounters projected for the Earth are greater than those at Mars, no significant design requirements need be added to a spacecraft with round trip capability to Mars. Although the heating is different and the spacecraft mass is greater at Mars than the Earth, heat shields can be distributed among spacecraft components to minimize the mass.

Table 1 shows a result that may be surprising at first glance: that even without aeroassist at Mars, the moons of Mars are more accessible to the Earth at biennial opportunities than is the Moon of the Earth. The chief difference is in the requirement to soft-land payloads on the lunar surface. With meager escape velocities of 11 and 6 m/s for Phobos and Deimos, the impulse required to "land" on these moons is negligible. Required maneuvers more resemble rendezvous and docking with a spacecraft rather than impulsive blasting into an out of a gravity well. As in the case of the asteroids, the PhD missions permit low impulse propulsion for the entire trip, opening the possibility of using solar electric engines, mass-drivers, tethers, and solar sails as the sources of propulsion.

The only advantages the Moon seems to offer are its proximity and launch window frequency of days versus months to years. However, once it has been established that humans can survive in space over long periods of time and once mining and exploratory operations begin and a pipeline of extraterrestrial materials starts to flow, it will probably not make much difference how close the source of materials is to the Earth. More significant

will be the energy required to process and transport them, and Phobos and Deimos clearly provide an advantage. If the moons of Mars were moons of the Earth, we would be there by now.

Two Apollo circumlunar flights were attempted before a lunar landing. Likewise, safety factors and economics suggest going to Phobos and Deimos before attempting to land humans on the surface of Mars. The 1984 Office of Technology Assessment report to Congress on the U.S. space program refers to missions "to the vicinity of Mars" rather than Mars itself. Former Apollo astronaut and U.S. Senator Harrison Schmitt (1984) foresees a possible Soviet human mission to Phobos by 1992.

Phobos and Deimos offer more than enough materials to industrialize space. Within their volumes, they contain the equivalent of 10 million 100-m-diameter (1 million ton) objects! The milligravity environment of the martian moons will permit certain industrial operations that may be more easily carried out than either in weightlessness or under the influence of a significant gravitational field. Dust, equipment, and people will not float away, yet structures need not be built to withstand a planetary or lunar gravity.

Tables 1 and 2 summarize the relative accessibilities of Phobos, Deimos, selected Earth-approaching asteroids, the lunar surface, and the martian surface. From a resource retrieval perspective, Table 2 expresses the approximate ratio of returned to invested mass from these objects given assumptions that may apply to resource retrieval missions during the early 21st Century. A total outbound Δv of 5 km/s is assumed in each case; this reflects the velocity increment required to escape from low earth orbit and subsequently land on or rendezvous with the target object. While individual opportunities

Table 2. Allowable Returned Mass of Processed Metals as a Function of Ballistic Return Velocity Increment (Δv)*

Return ΔV (km/s)	Tons of returned mass per ton of invested mass	Examples	Launch Date (or Frequency)	Round-Trip Travel Time
0.1	100	1982 DB, at special	2000-01	2 Years
0.2	49	times	(Every two decades)	
0.5	19.2	1982 DB, 1943	Occasionally (For a	2-3 Years
1.0	8.9	Anteros, 433 Eros, and 1982 XB	given object, every decade or more)	
1.9	4.0	Phobos and Deimos	Every 2 years	2 Years
2.4	3.0	Lunar Surface	Frequently	~7 Days
~5	1.0	Martian Surface	Every 2 Years	~2 Years
		1982 DB	Sept. 2001	4 Months
		Several Near-Earth Asteroids	Frequently	~1-5 Years

*See text for assumptions.

will vary, this number is probably within 1 km/s of actual cases, yielding comparable mass fractions for outbound journeys.

It is further assumed that the same cryogenic rocket with exhaust velocity 4 km/s is used for the return trip as for the trip out and that the rocket is refueled with liquid oxygen (and possibly liquid hydrogen) obtained at the target object. The final assumption is that any excess hyperbolic velocity of the incoming resources to the vicinity of the Earth can be eliminated either by planetary/lunar gravity assists (O'Leary, 1979) or by aerobraking at Earth using the raw materials retrieved from the target object [Gaffey and McCord (1977) have proposed the vacuum foaming of asteroidal metals as a reentry heat shield that could be subsequently used as resources on the Earth or in Earth orbit]. The resultant mass fractions therefore reflect only the impulse required to depart from the target object on an Earthward trajectory; this supposition remains to be tested by more detailed spacecraft design and mission concepts.

It is clear from inspecting Tables 1 and 2 and from the preceding paragraphs that Phobos and Deimos offer a unique blend of exploration, resource processing opportunities, accessibility, and frequency of launches. These factors combine to create a powerful incentive to conduct a detailed analysis of mission scenarios (O'Leary, 1985).

As for which moon to target, Singer (1984) has proposed Deimos to be the first manned destination, primarily because the outer moon's orbital period is nearly synchronous with Mars' rotation, allowing for more continuous telemetered operation of surface rovers. Phobos, on the other hand, provides some advantages. In terms of Δv, it is more accessible to the martian surface. Its position deeper within the martian gravity well grants it slightly more accessibility for circularizing after an aerobraking encounter but normally slightly less favorable return-to-Earth circumstances (unless periapsis maneuvers are performed for Mars escape). Phobos also provides a higher resolution view of the martian surface. By the time a manned mission is launched, we are likely to have more knowledge about the composition of Phobos than that of Deimos. A confirmation of water in the forthcoming Soviet mission to Phobos might be the deciding factor.

In reality, it will be desirable to visit both moons to assess both bodies scientifically. From an operational point of view, redundancy is desirable. In the long run, the two satellites could serve complementary roles: Deimos for astronomy, planetary coverage, reconnaissance, and control of Mars rovers; Phobos as a site for volatile mining if water is found there, sorties to and from the martian surface, and closeup surveillance of interesting sites. It may also be convenient for Soviet bloc nations to focus on one moon and western countries on the other in a cooperative effort. The Δv between the two moons is a convenient 747 m/s for two burn Hofmann transfers.

The next logical step is to define mission scenarios, list scientific objectives, and perform cost and performance trades with other options, such as the direct manned mission from Earth to the martian surface. O'Leary (1985) constructed a reference scenario of an early manned mission to Phobos and Deimos. Features of the scenario would include lower overall cost and safer operations than a manned Mars landing, more quality martian science by sequential exploration using unmanned rovers at

disparate sites telemetered from PhD, collection of Mars samples by unmanned vehicles and analyzing them in a PhD laboratory, sampling the martian moons themselves, and creating the infra-structure for processing fuels from PhD volatiles or oxides with rapid expansion thereafter. The only apparent missing feature of this first mission is the manned exploration of the martian surface. If, for political reasons, a manned Mars landing is warranted, the PhD scenario could include a sortie to the martian surface in a small vehicle at modest additional cost.

Many of the same ground rules for analyzing other manned missions—lunar bases, Mars landing mission, near-Earth asteroid missions—apply to the PhD case. Two studies carried out principally by the Schaumberg, Illinois group of Science Applications International Corporation (SAIC) provide the basic logistical requirements and costing assumptions for an initial lunar base (SAIC, 1984a), lunar base reconnaissance mission (SAIC, 1984b), a near-Earth asteroid mission (SAIC, 1984b), and a first manned Mars landing (Hoffman and Soldner, 1984; SAIC, 1984b).

In the last case, the investigators assumed a dual launch in 2003, aerocapture at both Mars and Earth, a 4-man crew, 30-day stay time, and minimal new technology. Their overall cost estimate of $39 billion (1984 dollars) could be reduced by a factor of 2 or more by eliminating the need for developing a man-rated Mars lander, including the fuel needed for an ascent stage to get out of Mars' gravity well (more shuttle flights, more OTVs). The manned Mars landing mission would more resemble a one-shot Apollo flight than the scenario of a sustained operation at a small base on PhD that would be manned initially and visited periodically for expanding the materials processing capability and upgrading the exploration program.

Because of increasing emphasis on the permanent presence of man in space and the developing technology to make that possible, the lunar base scenario may be more appropriate to the PhD missions than an Apollo scenario. One PhD workshop (O'Leary, 1984) considered an initial Phobos base consisting of two or three space station sized modules covered over with dust for radiation shielding (see artist's concept of Phobos base, Fig. 1). This modest facility could expand rapidly as we begin to industrialize space utilizing non-terrestrial materials. The economics of establishing and enlarging a PhD base appears to be more immediately feasible than those required to start and sustain a base on the martian surface deep within its gravity well. Table 2 shows that the ratio of returned mass to invested mass for delivery in free space is about 4 for Phobos and Deimos and only 1 for the surface of Mars. Phobos and Deimos will provide among the first of our non-terrestrial material resources.

The case for Phobos and Deimos enhances the case for Mars. We appear to have a situation of serendipity in science and economics. The PhD scenario requires new legitimacy previously not given it because of an inherent familiarity with doing things at the bottom of deep gravity wells. But the laws of physics and practical economics (*e.g.*, O'Neill, 1977) dictate we take a second look at our future priorities in space exploration.

Mission planners should investigate the PhD options in as much detail as is now being given to manned Mars landings and lunar bases. These tasks should not be difficult because methods for determining most of the assumptions, mission parameters, and

logistical requirements are common to all scenarios. The results will lead not to an either/or proposition about destinations involving irrevocable dead-ends, but a synergistic blend of missions that will grow rapidly. Phobos and Deimos appear to be at the focus of the initial step from which everything else will logically follow. The essence of martian exploration and space industrialization using non-terrestrial resources is embodied in the mysterious moons of Mars.

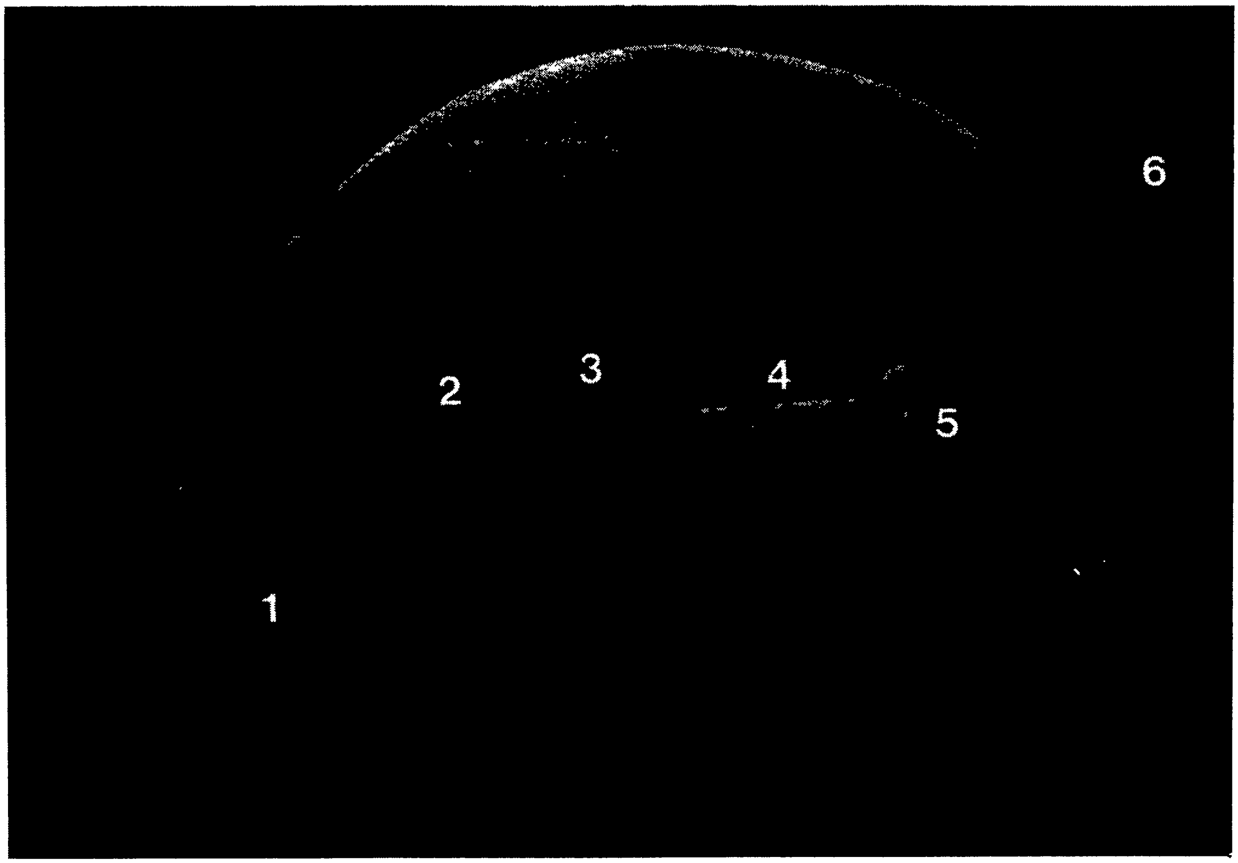

Figure 1. *1—Docking adapter for spacecraft; 2—Mars surface communications antenna; 3—airlock/access to buried modules; 4—modules based on space station technology; 5—multiple adaptor for future expansion (access port); 6—solar furnace for processing Phobos surface materials. Copy of painting by Michael W. Carroll.*

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THE MOONS OF MARS: A SOURCE OF WATER FOR LUNAR BASES AND LEO

Bruce M. Cordell

General Dynamics/Space Systems Division, Advanced Space Programs, C1-9530, P. O. Box 85990, San Diego, CA 92138

While oxygen is plentiful on the lunar surface, water and hydrogen are very scarce. The obvious source for these substances is Earth, although severe delta-V penalties are inevitable in this approach. Phobos and Deimos appear to be carbonaceous, volatile-rich moons. Up to 20% of these bodies may be loosely bound water; the total Phobos/Deimos water reservoir may be 10^{18} grams. The potential for Phobos and Deimos to contribute volatiles to the Moon and LEO is assessed. A concept is suggested for a mission originating at the lunar base that delivers large quantities of martian moon waters to the Moon. A Mars transfer craft aerobrakes at Mars before rendezvous with its satellites. A manned permanent station on Phobos and/or Deimos processes moon material to extract water. During Earth approach, aerobraking places the spacecraft into lunar trajectory. The advantages of this Moon-Phobos/Deimos loop include: (1) low delta-V's and cost compared to closed Earth-Moon circuits; (2) both LEO and the Moon are supplied with hydrogen and oxygen; and (3) this Moon-Phobos/Deimos loop provides an economic stimulus to further explore the martian moons and Mars itself.

INTRODUCTION

One of the major uses of the Moon will be as a source of raw materials. Life support systems, lunar base industrial processes, and spacecrafts and stations operating near the Moon and Earth will find many uses for lunar oxygen, metals, and silicates. However, water is unknown on the Moon and hydrogen is scarce; only traces (<50 ppm) of solar wind hydrogen are trapped within the regolith.

The possibility that ancient frozen cometary waters eternally shielded from the sun might have survived to the present at the lunar poles cannot be ruled out (Arnold, 1979). However, the total absence of moisture in the lunar samples suggests that possible polar waters should be viewed only as a potential bonus for lunar bases. Confirmation of lunar polar ice awaits the resumption of lunar exploration; thus, it is currently prudent to consider other possible sources of hydrogen to supplement the meager lunar supply.

An obvious source of hydrogen is Earth, due to its nearness to the Moon and abundance of hydrogen. Unfortunately, transportation costs resulting from Earth's well-known sizable gravitational well are substantial (characteristic velocities for Earth to LEO are 32,000 ft/s). These facts give impetus to the search for extraterrestrial and extralunar hydrogen reservoirs.

One attractive potential source of volatiles for cislunar operations is the population of Earth-approaching asteroids (O'Leary, 1977). Reflectance spectra for these objects and other evidence (*e.g.*, Gaffey *et al.*, 1977) suggest that some of these bodies are similar

to Type I carbonaceous chondrites. Up to 20% of these tiny worlds may be loosely bound water in various mineral assemblages. A few of them are excellent space targets because of their accessibility and negligible surface gravities.

It is suggested here that two asteroid-like objects, which happen to be in orbit around Mars, may become the hydrogen/water source that will stimulate the initiation of lunar resource utilization and the establishment of manned bases on the Moon's surface. The moons of Mars combine very high scientific interest and resource potential with extraordinary accessibility at a level unmatched by any other known extraterrestrial object [*e.g.*, see O'Leary (1984) and Cordell (1985)]. The total delta-V for an Earth-to-Phobos trip is less than that for a similar voyage to the lunar surface. Launch windows occur about every two years and one-way chemical propulsion times are several months. Phobos/Deimos round trip delta-V's compare favorably with those of any known Earth-approaching asteroids with 2-year launch windows (O'Leary, 1984). Additionally, a manned base on Phobos is an ideal platform from which to remotely study Mars itself (avoiding biological contamination and Earth-Mars radio time delay problems). Indeed, Phobos is an excellent staging area for manned missions to the martian surface.

Phobos and Deimos have low albedos, low densities, ancient surfaces, non-spherical figures, and reflection spectra that suggest they are relatively unmodified, volatile-rich, carbonaceous objects (*e.g.*, Veverka and Burns, 1980). Water may compose up to 20% of these bodies (*e.g.*, Hartmann, 1983) and could be retrieved for use in LEO/GEO or on the Moon. Propellant production facilities on Phobos/Deimos will make manned landings on Mars independent of terrestrial fuel supplies.

Furthermore, Phobos and Deimos are scientifically intriguing in their own right. Some cosmochemical theories claim that carbonaceous objects (*e.g.*, Phobos and Deimos) could not have formed at Mars' solar distance. Thus, the martian moons might be asteroids and would have required capture by Mars. Phobos and Deimos exploration will provide an opportunity to test these ideas and possibly anticipate the scientific and resource bonanza awaiting us in the asteroid belt.

Mars itself constitutes a potential volatile source for lunar bases and LEO. Remote sensing and *in situ* investigations of Mars have indicated that Mars probably possesses Earth-like volatile abundances (*e.g.*, Clifford, 1984). The potential for economically important mineral concentrations and precious ore bodies also appears to be very good—perhaps comparable with Earth (Cordell, 1984). Although Mars has probably not experienced plate tectonics (which is commonly associated with many mineral deposits on Earth) the existence of crustal swells, rifting, volcanism, impact cratering, and abundant water on Mars suggests that some ore-forming processes may have occurred during martian geological history. Terrestrial hydrothermal, dry-magma, and sedimentary mineral concentration processes have been identified that may have operated on Mars. In particular, tectonic similarities between mineral-rich Africa and portions of Mars suggest that the potential for mineral wealth on Mars is impressive (Cordell, 1984).

Despite the intriguing nature of the martian surface from scientific, resource, and adventure standpoints, Mars' gravitational well is deep enough to make direct transport of water or other substances to the Moon rather expensive.

THE FIRST MANNED MISSIONS TO PHOBOS AND DEIMOS

Initial Phobos/Deimos explorations are assumed to utilize advanced transportation systems (*e.g.*, Orbital Transfer Vehicles, OTVs) that are expected to be operational in the 1990s. This section presents a concept for the first manned mission to Phobos and Deimos utilizing trajectory data for the year 2001. Assuming reasonable funding levels, this is a conservative (*i.e.*, late) date. OTVs should be operational from the mid-1990s, and the LEO Space Station should achieve its growth configuration with full capability to support manned planetary missions. International cooperation and/or competition in space should certainly cause the initial manned Mars' moons expedition to edge toward the present (from 2001) rather than to recede into the future.

The only significantly new technology assumed is that associated with OTVs (*e.g.*, aerobraking capability) and human life support systems for long duration space missions. Although advanced techniques such as solar sails, tethers, and more powerful propulsion systems may indeed be available after the turn of the century, these initial manned Mars' moons missions have been conceived deliberately to be as simple and straightforward as possible.

Since this is a first mission, the general philosophy is to be safe, quick, and yet accomplish the crucial tasks. For this first manned visit to Phobos/Deimos, it is proposed to use a small crew of three, including one mission specialist astronaut trained as a geological scientist. The other two astronauts would be the commander/pilot and a physician/pilot. Both would actively support the geologic reconnaissance of Phobos and Deimos when in the vicinity of Mars and at other times would be engaged in monitoring spacecraft systems, crew condition, and cruise science.

For the 2001 opportunity, the astronauts would spend 60 days thoroughly mapping, exploring, and sampling the moons to ascertain their compositions and internal structures and to assess their resource potential. Complete high resolution imaging is essential for thorough topographic, structural, and albedo (later geologic) mapping. Remote sensing and imaging utilizes visual, infrared, radar, x-ray, and gamma-ray techniques. Internal structures are probed using geophysical packages (*e.g.*, active seismics) emplaced by the crew on the moons' surfaces. The acquisition of samples and cores of important type regions on the moons are of utmost importance for resource utilization plans.

A manned reconnaissance is preferred because exploration of Phobos and Deimos is essentially a geological task, *i.e.*, an activity best performed by astronauts actually on the moons. Highly trained, versatile astronauts can also be justified on an engineering basis (*e.g.*, equipment repair or modification). Indeed, the presence of men and women will make early manned Mars missions of great interest to the public—both in the U.S. and around the world. It is clear that the expansion of human activities to Mars, including the manned exploration of the martian satellite system and the actual first manned landing on Mars, will be among the most significant events in the entire history of our civilization.

It is assumed that the mission is to be assembled, launched, and later terminated at the LEO Space Station where inspection, testing, and analysis is performed on the samples and data from Phobos and Deimos. The delta-V's for the 2001 mission are

shown in Table 1. Major propulsive burns are required only for trans-Mars and trans-Earth injections, because aerobraking at Mars and Earth is used to reduce spacecraft velocity relative to each planet. Rendezvous with the low-mass moons is trivial compared with the descent/ascent requirement associated with landing on Mars itself.

Table 1. ΔVs for the 2001 Phobos/Deimos Mission

Maneuver	ΔV		Wp(Klb)	OTV
	Km/s	fps		
Earth escape (from LEO)	3.57	11,688	225	1
			64.3	2
Outbound midcourse	0.2	655	10.3	
Mars capture (with aerobraking)	0.0	0.0	-	
Phobos/Deimos rendezvous/docking maneuvers	0.6	1,964	28.6	
Mars escape (from Phobos)	3.24	10,608	105.1	
Inbound midcourse	0.2	655	4.4	
Earth capture (with aerobraking)	0.1	327	2.1	
Total	7.91	25,897		

For simplicity, a stacked OTV, multiple perigee burn strategy (*e.g.*, Friedlander *et al.*, 1984) is utilized for injection into Mars transfer and for Mars escape. All propulsive burns (except launch from Earth's surface to LEO) are accomplished by OTVs. The OTV assumed here is based on the configurations developed in a recent General Dynamics/Convair report (Ketchum *et al.*, 1984) for transport from LEO to GEO and the Moon. For the calculations, Isp = 485s for this cryogenic LH2-LO2 vehicle.

Trans-Mars injection (TMI) is accomplished using multiple perigee burns (*e.g.*, Friedlander, 1984) to minimize gravity losses and yet achieve the relatively large delta-V (see Table 1). Two OTVs (with propellant weight = 225,000 lbs.) are required for completion of the mission. The first OTV and approximately 30% of the second OTV's propellants are required for TMI.

The trip to Mars consumes 186 days. Upon arrival at Mars, aerobraking in Mars' atmosphere slows the craft and places it in an elliptical transfer orbit to either Phobos or Deimos. Circularization burns required to rendezvous with either moon are relatively minor (600 m/s).

About one OTV is budgeted for the return to Earth. The 360-day trip home involves a swing by Venus that lengthens the trip time but reduces Earth encounter velocities and moderates the demands on the OTV aerobrake. Aerobraking at Earth and rendezvous with the space station require minimal propulsive burns. If aerobraking technology becomes very reliable prior to the time of this first manned Phobos/Deimos mission, a direct return to Earth, with shorter flight time, may be preferable.

The relatively short 606-day total mission time minimizes space-related hazards for the crew while still providing adequate Phobos/Deimos exploration opportunities. To avoid deleterious biological effects on the crew, the habitability modules will be spun to simulate low (1/3) gravity. Phobos/Deimos surface gravities are biologically negligible

(1 cm/s2). Unfortunately, high solar activity near 2001 could make any manned interplanetary travel more hazardous.

This first Phobos/Deimos sortie could return about 500 lbs. of moon material to the space station (and maybe Earth) for analysis. Presumably, this will confirm and enlarge our understanding of these objects as volatile-rich carbonaceous bodies (*e.g.*, Veverka and Burns, 1980) with a number of relatively easily extractable substances, including water.

Prior to the launch of the first manned Phobos mission, promising technologies for extracting volatiles, particularly water, from supposed moon materials should be pursued intensely. This research and development phase will culminate in the return to Earth of the first samples from the moons of Mars. Specific methods will be empirically tested on the actual moon samples.

SUBSEQUENT MISSIONS TO PHOBOS AND DEIMOS

Should the demands for a source of water for activities on the Moon and in LEO become compelling and the desire to explore, utilize, and settle the martian environment become widespread, both goals could be accomplished by launching another more ambitious manned mission to Phobos and Deimos as early as 2005 (or two launch windows after the initial mission). This time, with full knowledge of the resource potential of these small but pivotal objects, astronauts would return with the following important objectives: (1) establish a permanent, human presence or base on these worlds; (2) construct and operate a water extraction plant (probably utilizing solar energy) as soon as possible; (3) in collaboration with research and development teams on Earth, experiment with possible technologies for producing propellants for spacecrafts from indigenous moon resources (*e.g.*, from water); (4) embark upon the first close-range, continuous, manned reconnaissance of the planet Mars ever attempted; and (5) aggressively pursue Phobos/Deimos science.

The specific technologies that will be utilized to extract water and process propellants on Phobos and Deimos will be dependent on the composition of the martian moons, available power sources, and weight constraints. The establishment of a water extraction system has not been considered in detail here and deserves study; this problem is likely to be particularly challenging because of the milli-g environment.

The scientific and strategic implications of Phobos/Deimos explorations, particularly with respect to the colonization of Mars, have been well elaborated upon by Singer (1984) and Adelman and Adelman (1984). Space precludes their repetition here, except to say that water on Phobos/Deimos can be the key to the exploration of Mars as well as a pivotal incentive to initiate major utilization of the Moon. Martian moon moisture can be used for life support, industrial processes, and rocket fuel (for interplanetary vehicles or descent/ascent to Mars itself) to support operations near Mars, Earth, and/or the Moon. Proper utilization of these martian resources will require the establishment of a permanent, relatively self-sufficient base on Phobos and Deimos. A small human presence near (and eventually on) Mars will facilitate the exploration, utilization, and settlement of Mars.

IRRIGATION OF THE MOON WITH MARTIAN WATERS

Once the Moon-Phobos loop is operating it should be possible to retrieve appreciable amounts of martian moon waters for use on the Moon and in LEO. Again, the intent here is to describe a simple set of operations, using primarily OTV propulsion and aerobraking technology, without resorting to more exotic transportation systems.

A typical water tanker mission could originate in low lunar orbit (delta-V's for this scenario are shown in Table 2). The event sequence would include the following: (1) multiple perigee burns by an OTV to insert the empty spacecraft tanker into Mars transfer orbit, (2) aerobraking, utilizing the martian atmosphere, (3) rendezvous with Phobos or Deimos requiring small impulses, (4) arrival at the manned moon bases where supplies are delivered, the OTV is fueled, and the water cargo is obtained, (5) separation from Phobos and insertion into Earth transfer orbit, (6) aerobraking at Earth and insertion into an elliptical lunar transfer orbit, (7) separation of a small tanker craft loaded with water that will aerobrake and rendezvous with the LEO space station (optional), and (8) propulsive burn to insert the spacecraft into a circular lunar orbit and rendezvous with the lunar space station.

Inspection of the total delta-V (Table 2) for the Phobos/Deimos-Moon loop versus the Earth-Moon round trip indicates that considerable advantages are obvious for Phobos/Deimos resource retrievals. The Phobos-Moon loops avoid descending into Earth's or Mars' gravitational wells and thus are not penalized in the way that Earth-Moon loops inevitably are. Additional advantages are evident in that at no time is the Phobos-Moon spacecraft ever immersed in a planetary atmosphere (except during aerobraking), thus

Table 2. ΔVs for Water Tanker Missions*, Phobos/Deimos-Moon vs. Earth-Moon

Earth-Moon Loop	ΔV		Phobos/Deimos -Moon Loop	ΔV	
Trajectory Leg	Km/s	fps	Trajectory Leg	Km/s	fps
Earth to LEO	9.7	31,758	Moon to lunar orbit	1.91	6,253
TLI from LEO	3.14	10,280	TMI from lunar orbit	1.6	5,238
Midcourse correction	0.10	327	Midcourse correction	0.2	655
Into lunar orbit	0.82	2,685	Mars moon rendezvous	0.6	1,964
Descent to Moon	2.10	6,875	TEI from Deimos	1.5–2.0	4,911–6,548
Ascent from Moon	1.91	6,253	Midcourse correction	0.2	655
TEI	0.82	2,685	Into lunar orbit	0.9	2,947
Capture into LEO	0.1	327	Descent to Moon	2.1	6,875
Descent to Earth	0.1	327	Ph/D to lunar surface and return	9.0–9.5	29,466–31,103
Earth to lunar surface and return	18.8	61,551	Ph/D to lunar surface and return	5.0–5.5	16,370–18,007
Earth to lunar station and return	14.8	48,455	Ph/D to LEO and return	7.9	25,865
Earth to LEO and return	9.8	32,085			

Note: Energy requirements to the lunar surface from Phobos/Deimos are one-fourth those from Earth
*Typical numbers for Hohmann trajectories.

conferring numerous design advantages on the tanker. Finally, it is seen that an enormous quantity of water can feasibly be delivered to the Moon from Mars' moons. To minimize delta-V costs, Phobos/Deimos-Moon water tanker missions should utilize conjunction-class trajectories.

It is assumed that advanced water loops involving the martian moons would utilize an unmanned single-stage OTV and a tanker with a fairly large capacity (*e.g.*, 1/10 that of an external tank or 450,000 lbs. of water). It is also assumed here that spacecraft propellants can be produced on Phobos/Deimos so that OTVs refuel only near Mars. Thus, the spacecraft assembly launched from lunar orbit consists of an empty tanker and a partially fueled OTV; only 30,000 lbs. of propellants are required to rendezvous with Phobos/Diemos bases. Upon arrival at Phobos, the OTV is refueled to capacity, and the tanker is filled with water. The OTV has a propellant capacity of 400,000 lbs (inert weight of 26.2 klbs.) and requires about 355,000 lbs. for insertion of the "martian iceberg" into low lunar orbit.

From lunar orbit a smaller descent craft may shuttle small amounts of water from the tanker, which would remain in lunar orbit until it ran dry and began the cycle again. Launch windows occur every two years, and thus one tanker would supply the Moon with over 600 lbs. of water per (Earth) day. Of course, in a very advanced loop, more or larger tankers could be used elevating this amount to whatever is considered optimum. Phobos and Deimos are not likely to run dry soon since their total water reservoir (assuming C1 carbonaceous chondrite composition) exceeds 400 million external tank capacities.

It might be useful to return only hydrogen (instead of water) from the martian moons since the same tanker could retrieve much more payload and only hydrogen is needed on the Moon, not oxygen. The main disadvantages of this are the following: first, problems with leaks of cryogenics during the flight from Mars, and second, LEO will require both hydrogen and oxygen to sustain its activities. Problems with insulation of cryogenics over long time periods will probably be solved fairly easily within 20 years if the demands for martian resources become obvious. On the other hand, if the shuttle (or its evolved derivative) were utilized to transport large amounts of water into LEO, the water would be electrolyzed in LEO; only hydrogen would go to the Moon. Since other volatiles are also depleted on the Moon and are probably available on Phobos/Deimos, it might be more efficient to return methane or ammonia if simple techniques can be developed to produce these substances from Phobos/Deimos materials.

The main disadvantage of Phobos-Moon loops is that launch windows occur only every two years, while Earth-Moon loops are very frequent. Travel times from Mars are also typically several months, while Earth-to-Moon times are a few days.

Nevertheless, the delta-V penalties of Earth-Moon loops and apparent abundance of volatiles on Phobos/Deimos make water retrieval missions to Phobos and Deimos appear surprisingly attractive. The added scientific, economic, psychological, and political bonanzas inherent in manned Mars explorations and settlements (*e.g.*, Singer, 1984; McKay and Stoker, 1984) are most impressive.

Simple water retrieval missions to Phobos and Deimos in support of space activities in LEO or at lunar bases may provide the economic incentive to begin the settlement of Mars as well as the industrialization of the Moon.

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THE PROBLEM OF WATER ON MARS

Steven W. Squyres

Theoretical Studies Branch, NASA/Ames Research Center, Moffett Field, CA 94035

The availability of water on Mars will be an important issue in planning the manned exploration of that planet. Water has played an important role in shaping the morphology of the martian surface. The present distribution of water on Mars is not completely understood. Important reservoirs include the regolith of the cratered highlands poleward of ±30° latitude, the polar layered deposits, and geochemically bound water in silicates. Other small reservoirs that may be simpler to exploit include atmospheric water and the polar perennial ice. Study of the water resource on Mars should be an important part of any precursors to manned exploration of the planet.

Ever since Schiaparelli's description of the now infamous "canals" on Mars, the subject of water on that planet has been of considerable interest, both within and outside the scientific community. While the canals of Schiaparelli were optical illusions, exploration of Mars to date has shown conclusively that H_2O, often in the liquid state, has played an important role in shaping the appearance of the planet's surface. With the renewed interest in manned exploration of Mars, the topic of water on Mars takes on considerable importance. Any manned mission to Mars will be much less expensive and more capable if water can be obtained on the planet's surface. While there is ample evidence for the action of water in the past, it is less clear where the water is at the present time. This paper briefly reviews the evidence for the former presence of large amounts of water on Mars and discusses the major sinks and present distribution of water on Mars.

One of the most startling and important discoveries of the Mariner 9 mission to Mars was the widespread evidence for modification of the martian surface by the action of liquid water (McCauley *et al.*, 1972; Milton, 1973). This evidence comes in the form of channels, which are often remarkably similar to terrestrial stream, river, and flood features.

The most striking channels are the outflow channels. These are most common in the equatorial regions of Mars and are concentrated along the northern lowland/southern highland boundary. They generally arise from the highlands and debouch onto the lowland plains. The source regions usually show very complex topography that earns them the name chaotic terrain. The appearance of the chaotic terrain strongly suggests removal of subsurface material and widespread collapse of topography. The channels arise fully formed from these chaotic regions and may extend for many hundreds of kilometers.

Although clearly the result of fluid flow, outflow channels bear only superficial similarity to terrestrial rivers. They are much more similar to the types of features formed by catastrophic floods on Earth (Milton, 1973; Baker and Milton, 1974; Baker and Kochel, 1979). The magnitude of the floods implied by the martian features is enormous. For

example, Carr (1979) has estimated a peak discharge of as much as 5×10^8 m^3 s^{-1} for a flood originating in Juventae Chasma and extending across Lunae Planum. A reasonable mechanism for triggering flooding of this magnitude may be geothermal warming of ground ice (*e.g.*, McCauley *et al.*, 1972; Sharp and Malin, 1975). It may be that the water released in the floods was originally contained in a confined aquifer capped by an impermeable lid of permafrost (Carr, 1979). With tectonic warping of the aquifer (as in formation of the Tharsis bulge), a hydrostatic head sufficient to cause breakout and flooding may have been developed. Once released, the floods were of sufficient size that they could have proceeded for enormous distances across the martian surface even under the present climatic conditions. The density of impact craters superimposed on the outflow channels indicates, however, that they date from fairly early in martian history (Malin, 1976; Masursky *et al.*, 1977).

A second type of channel apparently caused by flow of liquid water is the valley network. These are more similar to terrestrial drainage systems, consisting of narrow, often sinuous valleys with tributary systems. They are dissimilar to terrestrial stream systems in a number of ways, however, and are more similar to terrestrial drainage systems formed by sapping (Pieri, 1980). While formation by precipitation cannot be ruled out in a few cases, most valley networks apparently had a sapping origin.

All of the valley systems on Mars are found in the ancient cratered highlands. The density of superimposed impact craters indicates that formation of valley systems was concentrated in the earliest part of martian history, probably more than 4 b.y. ago. Because the fluid discharges implied by the valley systems are quite modest, it is unlikely that they could have formed under the present climatic conditions. They therefore provide strong evidence that the pressure and temperature of the atmosphere very early in Mars' history were significantly higher than they are today. This clement era did not extend past the earliest part of martian history.

A number of types of features on Mars appear to owe their formation to removal of subsurface ice. One is chaotic terrain, and another is fretted terrain, first described by Sharp (1973). It consists of smooth, flat lowlands separated from older uplands by a complex pattern of escarpments. Fretted terrain is found primarily along the northern lowland/southern highland boundary. It probably formed by escarpment recession due to removal of ground ice. This may have taken place either by direct sublimation of ice or by emergence of groundwater. Other smaller areas are found where more limited collapse has occurred, forming tablelands with scalloped edges, and small, closed depressions. These features are similar to thermokarst features formed by melting of ground ice at high latitudes on Earth.

Many impact craters on Mars possess unusual ejecta deposits consisting of overlapping lobes of debris apparently fluidized at impact. These have commonly been referred to as rampart craters (McCauley, 1973; Carr *et al.*, 1977). Somewhat inconclusive morphologic evidence suggests that the flow was not gas supported, but instead involved lubrication by interstitial liquid, probably water. The putative liquid may have been generated from ground ice by impact heating, or may have been present as liquid in the subsurface material prior to impact.

A number of features on Mars resemble patterned ground common at high latitudes on Earth. Patterned ground on Earth forms as a result of repeated diurnal and seasonal freezing and thawing of ice-rich soil, causing movement of material and segregation by ice content or sorting by particle size. Resultant patterns include circles, stripes, and networks of polygons. Networks of polygonal fractures are the most common form of patterned ground on Mars. They could perhaps be frost related, but their scale is one to two orders of magnitude larger than that of terrestrial patterns. The larger size may be an indicator of longer timescale temperature cycles (Helfenstein, 1980) or may simply indicate that the polygons formed by some tectonic process not related to ground ice.

All of the landforms discussed thus far only provide evidence for the former presence of ground ice. A variety of other landforms apparently owe their morphology to the present existence of ground ice in sufficient quantities to alter the rheology of the surface materials. With large enough amounts of ice present in a matrix of silicate particles, creep deformation of the ice can cause the entire mass of material to undergo quasi-viscous flow. In order to learn more about the present distribution of ground ice on Mars, Squyres and Carr (1984) have recently mapped the global distribution of such features using high resolution Viking Orbiter images.

Three types of features were mapped: lobate debris aprons, concentric crater fill, and terrain softening. Lobate debris aprons are thick accumulations of debris at the bases of escarpments. They have distinct convex-upward topographic profiles indicating creep deformation throughout the entire thickness of the material (Squyres, 1978). They commonly show surface lineations parallel to flow (probably caused by inhomogeneities in the source region) and compressional ridges where the flow is obstructed. Their morphology is very similar to that of terrestrial rock glaciers. Concentric crater fill is apparently the same material confined within impact craters. Inward flow of the material gives rise to radial compressive stresses that produce crater fill with a pattern of concentric ridges. Terrain softening is a distinctive style of landform degradation apparent only in high resolution orbital images. It is revealed by extreme rounding of features that are elsewhere sharp (*e.g.*, crater rims) and marked convexity of slopes that are elsewhere straight or concave (*e.g.*, crater walls, erosional scarps). Lobate debris aprons and concentric crater fill probably require substantial amounts of interstitial ice. Terrain softening, because it preserves the large-scale components of the original topography, probably requires less ice.

Where these deformational landforms are observed, they are inferred to indicate recent or present existence of large amounts of ground ice. This inference is based on the following reasoning. (1) Ice may be present in sufficient quantities that its removal would have caused collapse, which is generally not observed (ice contents upwards of ~30% by volume are typically required for creep deformation in rock glaciers on Earth). (2) Removal of the ice would have caused a "stiffening" of the material, so that subsequent mass wasting and impact erosion would not have allowed the rounded morphology to persist. (3) Many of the lobate debris aprons and deposits of concentric crater fill are devoid of impact craters, indicating that flow sufficient to disrupt the surface morphology has taken place recently. Mapping of these features may therefore provide some of the most unambiguous evidence available for the presence of ground ice deep in the martian regolith.

The most striking characteristic of the distribution found is the nearly complete absence of all three classes of features from the equatorial latitudes. Virtually no examples of lobate debris aprons, concentric crater fill, or terrain softening are found equatorward of 30° latitude in either hemisphere. In the northern hemisphere, lobate debris aprons are most common in Tempe Fossae, Mareotis Fossae, the Phlegra Montes, and particularly in the fretted terrain between longitudes 280° and 0°. Concentric crater fill is also found in these areas, but is most common in Utopia Planitia. Terrain softening is most common in the portion of the cratered highlands lying between the fretted terrain and 30° north latitude. In the southern hemisphere, lobate debris aprons are common in the massifs surrounding the Argyre and Hellas basins. Concentric crater fill is observed primarily in the area east of Hellas. Terrain softening is observed in virtually all the high resolution images south of -30° latitude.

To summarize, all observed regions of old, heavily cratered terrain lying at latitudes poleward of ±30° have undergone terrain softening. This distribution may mean that the deep regolith equatorward of ±30° has been largely devolatilized, while that at higher latitudes still retains most of its original complement of outgassed H_2O. One possible explanation for the devolatilization is simply that ground ice at low latitudes is not in equilibrium with the atmosphere and that the regolith is too coarse grained to provide an effective diffusion barrier that would prevent its escape. The scale of topographic deformation observed suggests that this high ice content may extend to depths of 1 km or more. The amount of ice present in this reservoir is difficult to estimate, but it may form the largest present reservoir of H_2O on Mars.

The polar deposits are another large reservoir of water on Mars. The martian polar deposits exhibit a complex stratigraphy, but from the simplest standpoint can be considered to consist of three units. From base to top, these are the layered deposits, the perennial ice, and the seasonal frost cap. The layered deposits were first recognized in Mariner 9 images of Mars (Murray *et al.*, 1972; Soderblom *et al.*, 1973; Cutts, 1973). They are found at both poles and extend equatorward to 85°-80°. Individual layers are typically 10-50 m thick and extend laterally for hundreds of kilometers. The total thickness of the deposits is difficult to estimate accurately but may be 1-2 km in the south and 4-6 km in the north (Dzurisin and Blasius, 1975). The layered deposits are overlain by the perennial ice. At the north pole, the perennial ice reaches almost to the perimeter of the layered deposits, while in the south it covers a smaller area. Typical surface temperatures at the north pole in summer are 205 K (Kieffer *et al.*, 1976). This is substantially higher than the saturation temperature of CO_2 at the martian surface pressure and is clear evidence that the northern perennial ice is H_2O. The situation at the south pole is more complex (Kieffer, 1979), and the evidence there may indicate a thin layer of CO_2 frost underlain by H_2O ice. The thickness of the perennial ice is not well determined. The inferred thermal inertia implies a thickness of at least 1 m (Davies *et al.*, 1977), and the lack of observable topography suggests a maximum thickness of a few tens of meters. The seasonal frost cap consists of CO_2 and is deposited at each pole during the winter. It typically extends from the pole to 45°-40° in each hemisphere at its maximum extent.

The perennial ice is the most obvious reservoir of H_2O in the polar regions. The layered deposits may contain much more H_2O, however. The deposition of the layered deposits was first described by Cutts (1973). He noted that a substantial fraction of the atmospheric CO_2 is displaced into the seasonal frost cap each winter. He suggested that this poleward flux of CO_2 could entrain dust particles put into suspension by planet-wide dust storms. Entrained particles would then become embedded in the seasonal cap and be left behind when the cap evaporated in summer. Later models (Howard, 1978; Cutts *et al.*, 1979; Squyres, 1979; Cutts and Lewis, 1982) have recognized the importance of the perennial ice in the process. The role of the perennial ice is indicated by the limited extent of the layered deposits. Seasonal dust deposition should take place at all latitudes covered by the seasonal caps, and indeed there is evidence in the Viking orbiter images for dust mantling down to the mid-latitudes. The layered deposits, however, are limited to within 5°–10° of the poles, which, at least in the north, coincides with the present limit of the perennial ice. It seems, then, that only dust that is deposited onto the perennial ice is incorporated into the layered deposits. The layered deposits are interpreted by most workers to be composed of a mixture of dust and H_2O ice. The layering may result from periodic climatic changes that vary the extent of the perennial ice and the dust-carrying capacity of the atmosphere (Murray *et al.*, 1973). The ice content of the layered deposits is not known, but values as high as 85% have been suggested (Toon *et al.*, 1980). They may therefore be another very important reservoir of H_2O on Mars.

There are several other ways in which water can be stored or lost on Mars. First, there is a small amount of resident H_2O in the martian atmosphere. Compared to other sinks, however, the water content of the atmosphere is quite small. Planet-wide, the largest concentrations occur near the north polar regions just after summer solstice, but even the largest column abundance measurement is only about 100 precipitable microns (Jakosky and Farmer, 1982). The maximum amount of water observed in the entire martian atmosphere at any time during the year is equivalent to just 1.3 km^3 of ice. Some water is adsorbed onto the surfaces of regolith grains. This water is available for exchange with the atmosphere, but its volume is probably also small. A large amount of water may be locked up geochemically as water of hydration in a variety of minerals. Finally, a significant amount of water has been lost to space from the atmosphere. The loss has taken place primarily by photodissociation of atmospheric H_2O and escape of H and O.

It is clear that water has been important in shaping the morphology of the martian surface, and it is clear that there is still a substantial amount of water on Mars today. It is less apparent how best to obtain the water that is present. In terms of total volume, the largest reservoirs of water on Mars are probably ground ice in the regolith poleward of ±30° latitude, the polar layered deposits, and geochemically bound water in silicates. In terms of accessibility, the best reservoirs are probably the atmosphere and the polar perennial ice, although the latter suffers from a climate that is extremely harsh, even by martian standards. When the time comes to make plans for manned martian exploration, it will be necessary to evaluate the costs and tradeoffs involved in extraction of water

from each reservoir. For example, extraction of water from the atmosphere is attractive in principle, but requires turbine systems with high efficiency and throughput. Water may be available in the mid-latitude regolith in large quantities, but extraction would require that substantial effort be put into excavation. Water extraction from the polar regions would require operation in a very inhospitable environment. The most hospitable regions on Mars, near the equator, are the least attractive from the standpoint of water availability.

Before any plans are made for exploitation of the martian water resource, it will be necessary to study the present distribution and transport of water on Mars much more thoroughly. Problems of particular importance include the details of exchange of H_2O between the atmosphere and the regolith, determination of the ice content of the polar layered deposits, and verification of inferences made about the ice content of the regolith. The first steps toward these objectives will be made by the upcoming Mars Observer mission. Study of the water resource should also be an important part of any post-Mars Observer precursors to manned exploration.

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